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Extension of energy crops on surplus agricultural lands: A potentially viable option in developing countries while fossil fuel reserves are diminishing

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ABSTRACT

The rapid depletion of fossil fuel reserves and environmental concerns with their combustion necessitate looking for alternative sources for long term sustainability of the world. These concerns also appear serious in developing countries who are striving for rapid economic growth. The net biomass growing potential on the global land surface is 10 times more than the global food, feed, fiber, and energy demands. This study investigates whether the developing countries have sufficient land resource to meet the projected energy demand towards 2035 by planting energy crops on surplus agricultural land after food and feed production. The annual yields of four commonly grown energy crops specifically jatropha, switchgrass, miscanthus, and willow have been used to make scenarios and estimate land requirements against each scenario. This paper first performs literature reviews on the availability of land resource, past and future trends in land use changes, demand of lands for food production, and potential expansion of croplands. The energy demands towards 2035 are compiled from energy scenarios derived by the International Energy Agency (IEA) and the British Petroleum (BP). This paper also reviewed bio-physiological characteristics of these energy crops to determine whether they are cultivable under tropical climatic conditions in developing regions. This paper found that projected energy demand through 2035 in developing regions could be provided by energy crops grown on a portion of surplus croplands or upgraded grasslands (27% and 22% respectively for miscanthus scenario). Sustainable land management practices, improved agricultural productivity, and adopting suitable energy crops cultivation can potentially supply increasing energy demands.

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1. Introduction

Conventional fossil fuel sources such as oil, coal, and natural gas account for 81% of the global primary energy consumption in 2010 [1]. The recoverable proven reserves of these fossil sources are projected to be diminished by about 40 years, 55 years, and 130 years from now at the current rate of use for oil, natural gas, and coal respectively [2]. This projection shows that the proven fossil fuel reserves will be completely exhausted after 70 years at the current rate of consumption, and most likely earlier considering the increasing trends of demands [3]. The current pattern of energy supply cannot be sustained in the near future because of the depletion of fuel reserves and also environmental impacts of using these fuels [4]. The surging demand of food, feed and energy for the increasing global population is provoking the earth's ecosystem and its limited resources [5]. The negative environmental consequences and declining fossil fuel reserves have increased interest in renewable bioenergy sources.

Bioenergy is a renewable source of energy, and its sustainable use emits net zero CO_2 to the atmosphere. The increasing use of this energy source could reduce the GHG (greenhouse gas) emissions and contribute to achieve the sustainable development goals [6]. The major inputs into bioenergy production are land and water resources, which are also essential for producing food, feed and other essential plant commodities. The competitive feature of resources for biomass puts bioenergy under scrutiny before determining their real potential which is sustainable. On the one hand, biomass for energy production is an attractive substitute for fossil fuel sources, and on the other hand, its competing application of lands and water resources poses doubt on its potential.

One study [3] finds that the global energy demand projected by the IEA (International Energy Agency) in the reference scenario[1] for the year 2030 could be provided from the lignocellulosic bioenergy crops grown sustainably on unarable degraded lands. This study claims that the land and other resources would not compete with the increasing food production. They say that the energy demand can be met through afforestation of degraded areas, and investment for energy from biomass is cheaper than investing in fossil based energy. Another study [5] finds that the maximum primary energy potential from biomass in 2050 is 161 EJ/yr on projected surplus cropland and land extended from grassing areas. Smeets et al. [7] estimated that bioenergy potential on surplus agricultural land (i.e. land not needed for food, feed etc production) equaled 215–1272 EJ/yr, depending on the advancement of agricultural technology. Hoogwijk et al. [8] estimated that energy potential from energy crops on surplus agricultural land is as much as 998 EJ/yr. Another study [9] says, the global potential for bioenergy production ranges from 130 to 410 EJ/yr on abandoned degraded land. The potential of biomass energy depends primarily (besides other factors) on land availability. Currently the land area utilized for growing energy crops for biomass fuel is only 0.5–1.7% of global agricultural land [10]. Study also suggests that only 10% increase in biomass production through irrigation, manuring, fertilizing, and/or improved management in land use could serve the entire global primary energy demand. In the regional scale, one study [11] reveals that the biomass potential in the European Union region is sufficient enough to ensure the bioenergy target by 2020; however, mobilization of biomass plantation would be the key challenge. IPCC (Intergovernmental Panel on Climate Change) special report on renewable energy [12] suggested that, in 2050, the bioenergy potential can be in the range of 50 EJ/yr in the scenario of high food and fiber demand, and reduced agricultural productivity, to about 500 EJ/yr by maintaining key sustainability criteria.

Several studies have estimated the sustainable biomass potential for bioenergy production in global scale and in-line with various scenario and assumptions; however, far too little attention has been paid on bioenergy potential in developing countries. In this study, we examine the extents of land availability for meeting the projected energy demand in 2035 in developing countries through selected energy crops scenario grown on surplus croplands or lands upgraded from pasturelands or grasslands. We review literature for land availability, their current and projected uses, and historical changing trends. We also review the bio-physiological characteristics of four energy crops to see whether they are suitable to grow under tropical climate conditions in the developing countries. Based on the insight gained from the literature review, we made a set of assumptions on which we determine the extents of surplus land availability for meeting the projected demands. This article also highlights the sustainability issues related to bioenergy production concerning economic, social and environmental impacts on them. Land management practices, increasing of productivity, and reconciliation of land and water sharing would be the main challenges to realize the potential.

2. Materials and methods

In the first part, relevant literature were reviewed to explore the current status on land availability, land use pattern, crops and energy production and their present and projected demands. Historical trends in land use changes, crop yields, per capita land use were also reviewed from statistical database and literature sources. In the second part, a set of assumptions were made based on the information and insight gained from the reviewed literature to determine the extents of land availability for growing selected energy crops to meet the projected demands. Characteristics of four commonly used energy crops are reviewed for examining their adaptation suitability in developing regions, which are mostly fallen under tropical climate zones. Developing regions are selected as those geographic areas which are classified as developing economic zones according to United Nations Statistics Division (UNSD) [13].

2.1. Review of literature

2.1.1. Land availability on the global scale

Total land surface of the globe is 13.2 Gha, and among them 5.0 Gha has been in use for food production for direct human consumption and animal grazing for livestock [14]. FAO classified the total land area into four major land-use categories: arable land, permanent meadows and pastures (grasslands), forest area, and other

[1] Reference scenario took into consideration only those policies and measures that had been formally adopted by mid-of the studied year (2006).

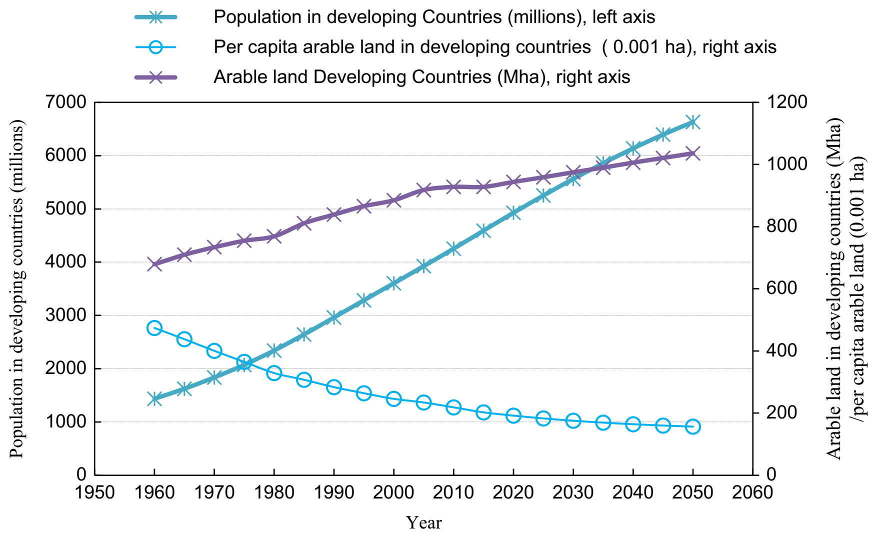


Fig. 1. Expected arable land expansion toward 2050.

land.[2] This allocation is inclusive of all land masses of the earth that leaves no land area unclassified. FAO estimates that total land area under crop production in 2010 was 1545 Mha and would be 1645 Mha in 2050 [15]. This study says that although few countries have reached or are about to reach the limits of their available land for agriculture, at the global level there is still sufficient land resources to feed the world's population for the foreseeable future in line with the estimated yield growth [15]. Arable land is expected to expand by 98 Mha in 2050 from the base period of 2005 (Fig. 1). Among them, 118 Mha is expected to increase in developing countries, and 21 Mha is expected to decrease in the developed countries. The IPCC study estimates that the total potential cropland to be 2.49 Gha in 2050, and among them 0.90 Gha was in use in 1990 for food production and additional 0.42 Gha will be required to feed the human population by 2050 [16,17]. According to IPCC, 1.28 Gha of cropland will remain extra after food production in 2050 and will be available for biomass production. Analysis of global Agro-Ecological Zones (GAEZ) data shows that potential land resources for crop production will remain sufficient, but their assertion is subjected under many issues. One issue is much of the potentially arable land is located in Latin America and sub-Saharan Africa, far from the agriculture infrastructure. Another study [17] says that global net potential croplands for rainfed cultivation is 3.82 Gha, from which 1.46 Gha were being used for food production in 1994. This study implies that 2.36 Gha of croplands will be available for biomass production, which will not compete with lands that is under food[3] production.

Birdsey et al. [16] show the extent of all land available under different vegetation categories (Table 1). They assert that the area under tropical savannas and temperate grassland will exceed 3.5 Gha and these areas are the best candidate for forest planting.

Ladanai and Vinterback [10] in their work present land distribution of different land use types of global total land area (Fig. 2(a)). According to their compilation, total forest area (natural and planted) coverage is 5.1 Gha, and among them 0.2 Gha is planted forest. This study shows that 3.5 Gha of land area is under permanent meadows and pastures with herbaceous forage crops, either cultivated or wild growing and is being used as grazing land or wild prairie. This article also observes from work based on [8] that surplus agricultural land has an enormous potential to produce bioenergy with surplus land area of 2.53 Gha.

Table 1
Estimation of global vegetation areas.

Vegetation type	Area (Gha)[a]
Tropical forests	1.76
Temperate forests	1.04
Boreal forests	1.37
Tropical savannas	2.25
Temperate grasslands	1.25
Deserts and semi-deserts	4.55
Croplands	1.60

[a] These data correlate with the FAO classifications as follows: tropical forests, temperate forests and boreal forests correspond to forest land; tropical savannas and temperate grasslands correspond to permanent meadows and pastures; desert and semi-deserts correspond to other land; and croplands corresponds to arable land of FAO classification).

According to FAO database [18], 3.35 Gha land area is remained under permanent meadows and pastures (Fig. 2(b)). Another study [19] shows that total human-induced degraded land area is 3.5 Gha of which 0.8 Gha is very severe, and 2.7 Gha is severe degraded lands. The poor quality degraded land can potentially be used for biomass production through afforestation of the degraded and wasted lands. IPCC [20] estimated that 1.28 Gha of degraded land can be utilized for energy production through afforestation, and this land is only 30% of the total degraded land area.

2.1.2. *Geographic areas owing to developing countries and land distribution*

The United Nations Statistics Division (UNSD) [13] broadly categorized geographic areas into developed and developing regions. The sub-continental economic groups of countries which are classified as developing regions are represented by their corresponding continental regions in this study. The four continental regions namely Africa, Asia, Latin America and the Caribbean, and Oceania, and sub-continental economic groups under their cover are given in Table 2.

[2] **Arable land** includes all lands that are under agricultural crop production; **permanent meadows and pastures** are those lands which are under permanent herbaceous forage crops (grasses); **forest land** is the land area spanning more than 0.5 ha and trees more than 5 m height and canopy cover more than 10%; **other land** is the land that are not classified into either of the three categories e.g. urban areas, protected lands, and unused areas such as glaciers, barren land and deserts.

[3] When the word 'food' is not accompanying the words 'feed, fiber, other use etc.' the word 'food' itself represents feed, fiber, other use etc. throughout this study.

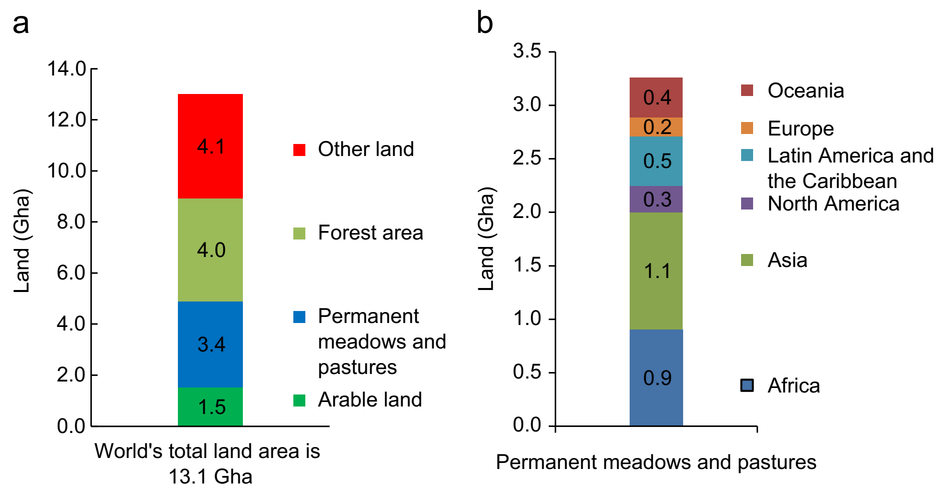


Fig. 2. Global landmass distribution: (a) all major land categories (b) permanent meadows and pastures.

Table 2
Composition of geographic regions by economic sub-regions.

Continental regions	Sub-continental economic groups representing developing countries
Africa	Eastern Africa Middle Africa Northern Africa Southern Africa Western Africa
Asia	Central Asia [a]Eastern Asia (excluding Japan, China, South Korea) Southern Asia South-Eastern Asia Western Asia
Latin America and the Caribbean	Caribbean Central America South America
Oceania	Oceania (excluding Australia and New Zealand)

[a] According to UNSD, China and South Korea are under developing regions but this study excludes them.

Table 3
Land distribution (land in use) in the developing regions 2011 (Gha).

Land type	Continental regions				
	Africa	Asia	Latin America and the Caribbean	Oceania	Total (Gha)
Arable land	0.25	0.418	0.124	0.001	0.793
Permanent meadows and pastures	0.907	0.696	0.448	0.001	2.052
Forest area	0.677	0.349	0.850	0.036	1.912
Other land	1.138	0.651	0.257	0.017	2.063

The land distribution (it does not indicate the potential land rather indicates land in use) in developing regions are presented in Table 3.

2.1.3. Demand of croplands for food, feed, fiber, and other uses in developing regions

The demand of the food and other agriculture commodities are obvious and their supply cannot be restricted by any other applications irrespective of importance. The United Nations (UN) estimates that the population in developing countries (except China) will reach 6.6 billion by 2050, an increase of 2.3 billion from the population level in 2010 [15]. FAO estimates, still in 2010, about 900 million people in the world (mostly in developing countries) have lack of access to sufficient food. The food production will need to increase by almost 100% from the production level in 2010 in developing regions by 2050 to cope with the increasing population and to ensure the food consumption level to 3070 kcal (12.5 MJ) per person per day. According to FAO, total cereal production in 2012 was 950 Mt in developing regions and additional 900 Mt will require in 2050. In 2050, total 1850 Mt cereal production requires a land area which may not be more than 0.49 Gha even if the production yields would not increase from the current state.

Table 4
Positive and negative impacts of converting land for energy crop production. [22].

Land type that to be converted	Impacts
Cropland	Extremely negative effect found on the economy and food security
Abandoned agricultural land	No negative impact on the economy and food security
Natural forests	Affects on environments and ecosystems
Planted forests	Negative impact on the economy
Degraded natural vegetation	Restores vegetation cover
Degraded marginal lands or unareable lands	Improves valuation of the lands

Table 5
Global land use changes (Mha)1987–2006 [21].

From–To	Forest	Grassland	Cropland	Urban areas	Losses	Gain	Net change
Forest	3969.0	3.0	9.8	0.2	−13	5.7	7.3
Grassland	1.4	3435	1.0	0.2	−2.6	5.0	2.4
Cropland	4.3	2.0	1513	1.6	−7.9	10.8	2.9
Urban areas	0	0	0	38.0	0	2.0	2.0

2.1.4. Historical trends in meeting increasing land demand

The additional crop production can be achieved either by bringing extra land under cultivation or improving the yield or by a combination of both. Research shows that, in last 50 years, yield improvement was the main driver to increase the major cereal production rather than the expansion of arable land.

Historical trends of land conversion and crop yields improvements are discussed in the following sections.

2.1.4.1. Land conversion. The land use change occurred continuously over historical times on the earth. The main drivers of land use change were increase of population and population density, increase of productivity, higher income and consumption patterns, and technological, political and climate change. The major changes of land use in global scale in the past are happened in forests, especially by conversion to cropland and grassland (Table 5) [21]. Increase in forest area is occurred in the Eurosian boreal forest and part of Asia, North and Latin America due to new planted forest. Some croplands also have been converted to forest land and to urban development around major cities of the world.

There are various options that can be used to convert existing land into energy crop production. This approach, however, has some negative impacts such as land degradation, loss of biodiversity, disruption of biophysical cycles such as water and nutrients cycle. It will be more beneficial that agricultural activities in these converted land increase food security and in the same way afforestation improves environmental and ecological balance and increase raw materials supply for energy and industries. The land conversion/alteration methods and their impacts are described in Table 4.

Land transformation during the past 300 years are presented in Fig. 3 [23,24]. The study suggests that, among other things, a global increase in cropland area occurs from 265 Mha in 1700 to 1471 Mha in 1990 while the pasture areas has increased from 524 Mha to 3451 Mha, which is more than six fold increase. The cropland increase takes place at the expense of natural grassland and to a lesser extent of forests.

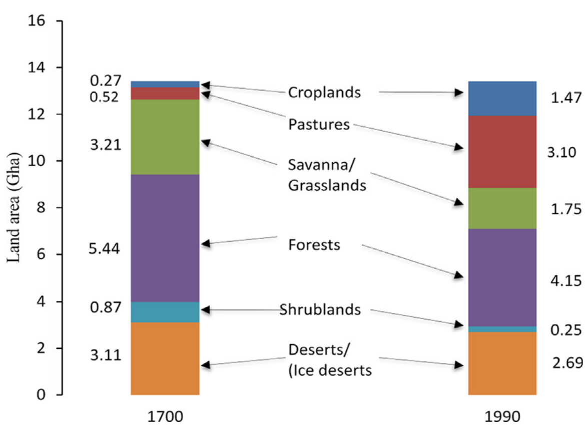


Fig. 3. Land transformation during the past 300 years 1700–1990.

2.1.4.2. Intensification of agricultural production. The main driver which significantly downturn the increasing trends of cropland areas is the increase in efficiency of food production [21]. Cereal yields have been increased very significantly over the last 25 years (17–40%) in different regions of the world. In Africa, the production yields still remained low and have a large room to increase the land use efficiency. One hectare arable land could produce annually 1.8 t of plant products in 1980, whereas the same land produced 2.5 t of products in 2007. Though the average cropland per farmer has been decreased since 1960, the aggregate food production per farmer has been increased. According to an estimate by the World Bank and OECD-FAO, yield improvements of the principal cereals (rice, wheat, and maize) were the main driver for the increased production rather than area expansion over the last 50 years (Table 6) [15]. FAO predicts that, from the base year of 2005, only 17% of the production increase is expected to come from land expansion; the remaining 83% is expected from higher yields and crop intensity.

2.1.5. Potential land for crop production 1998–2030

Bruinsma [25] estimated that total 2.782 Gha land areas are suitable for agricultural production in the developing regions (Table 7). Among total potential agricultural lands, 30% of the lands were in use for agricultural production in 1998 and 34% will be in use for the same purposes in 2030. This study shows that 1831 Mha of land which is suitable for crop production will remain outside of crop production in 2030 in developing countries. Eisentraut [26] shows that 2.052 Gha of land will remain as meadows and pastures land in developing countries, which neither conflict with crop production nor forest conservation (Table 8).

2.1.6. Projected primary energy demand in developing countries

BP (2012) has made a global energy outlook to 2030 by taking account of developments over past years and based on projected changes in policy, technology and economic conditions [27]. BP outlook predicted that the primary energy consumption in developing regions is to grow by 1.9% per year over the period of 2010–2030. Total

Table 6
Average annual growth rates in major cereal production 1960–2011[15].

Period	1960–2011
Production growth	2.4%
Yield contribution	1.9%
Area expansion contribution	0.5%

Table 8
Meadows and pastures land [26].

Regions	Africa	Asia	Latin America and the Caribbean	Oceania	Total
Permanent meadows and pastures lands (Mha)	907	696	448	1	2052

Table 7
Potential land and land in use for crop production in the past and projected.

Regions	Potential land for crop production (Mha)	Land in use for crop production (Mha)			Percent in-use as of total potential land (%)		
		1998	2015	2030	1998	2015	2030
Africa	1130	314	351	381	(28%)	31%	(33%)
Asia	586	305	313	328	(52%)	54%	(56%)
Latin America and Caribbean	1066	203	223	244	(19%)	20%	(23%)
Developing regions total (Mha)	2782	822	889	951	(30%)	(32%)	(34%)

Table 9
Primary energy demand in developing countries toward 2030 (EJ/yr) projected by BP.

Year	2010	2015	2020	2030
Primary energy demand (EJ/yr)	181	200	220	263

Table 10
Primary energy demand in developing regions in the new policies scenario (EJ/yr).

Regions	Year				
	2010	2015	2020	2030	2035
Africa	29	32	34	39	41
Asia	90	105	119	149	167
Latin America and the Caribbean	25	28	31	36	38
Oceania	15	15	16	18	20
Total (EJ/yr)	159	180	201	242	266

Table 11
Primary energy potential from projected crop and livestock residues (EJ/yr).

Year	2010	2015	2020	2030	2035
Energy from crop and livestock residues	41	44	47	53	56

primary energy consumption in developing regions is projected to increase by 45% between 2010 and 2030 (Table 9). According to this outlook, the primary energy demand was 181 EJ in 2010 and would be 263 EJ in 2030.

According to IEA's world energy outlook-2012, primary energy demand in developing regions will increase by 67% between 2010 and 2035 in the new policies scenario[4] [1]. The energy demand increase even higher in current policies scenario than the new policies scenario. The yearly increase of energy demand is to be 2.1% for new policies scenario over the period of 2010–2035. The annual energy demand in 2035 would be 266 EJ in the new policies scenario (Table 10).

2.1.7. *Energy potential from agricultural residues*

The projected crops and livestock will give a huge amount of residues, and they have the potential to be utilized as an energy feedstock [26]. Rahman and Paatero [28] have developed a methodology to quantify the primary energy potential for agricultural residues, which will not conflict with food, feed, and fiber applications. This method computes the energy potential from projected crops and livestock between 2010 and 2035 and presents in Table 11.

2.1.8. *Biomass pathways for energy*

Bioenergy can be produced in many potential pathways shown in Fig. 4. The available land beyond the food production can be used for ever growing and much needed bioenergy and bio fuel production. The technical potential of global primary biomass energy can be analyzed by considering suitable biomass species. Study finds that forest biomass production as the energy sources can be the preferable option for temperate regions but not for tropical and subtropical regions [26]. Johansson et.al. show that energy crops are preferable to the other biomass option for producing biomass for energy [29]. The energy crops option is driven by the higher productivity and shorter time span between plantation and harvest by compared to forest woods [17]. Considering their favorable role, this study will only consider energy crops on surplus croplands and residues from agricultural products as the potential energy sources to meet the projected demands (Fig. 4).

[4] The new policy scenario, according to world energy outlook 2010, takes into account the broad policy commitments that have already been announced by June 2010

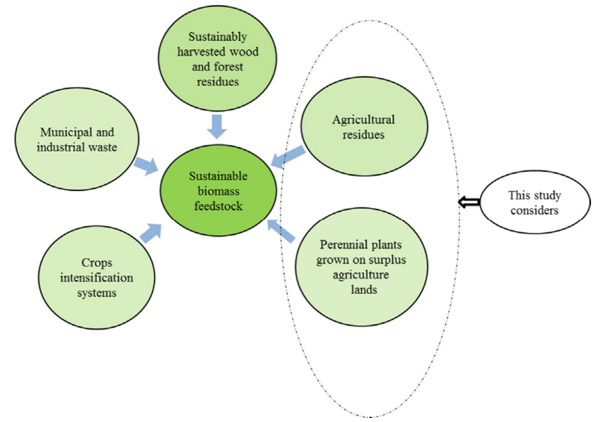


Fig. 4. Possible biomass feedstock supply which neither conflicting food production nor land use.

Table 12
Biodiesel productivity of various oil crops [36,37].

Crops	Annual oil yield (L/ha)	Annual biodiesel productivity (kg/ha)
Corn/maize	172	152
Soybeans	636	562
Hemp	363	321
Canola/rapeseed	974	862
Sunflower	1070	946
Palm oil	5366	4747
Castor seed	1307	1156
Camelina	915	809
Groundnut kernel	450	890
Jatropha	741	656

2.1.9. *Energy crops*

The energy crops are those woody or herbaceous plants and grasses which are typically densely populated high yielding plant species. They grow under low cost and low maintenance environment and possess higher energy values. Ideal energy crops should be characterized with high yield, low energy input and low cost, and biomass should be composed with the least amount of contaminants. The suitable energy crops also require low soil nutrient, water, pesticide, and fertilizer. The most widely cultivated energy crops are Jatropha, Miscanthus, Switchgrass, and Willow [30–32]. These four energy crops give higher yields and can even grow in unarable and marginal land. Crop rotation periods for the fast growing hardwood trees (willow) are usually 3–10 years; herbaceous grasses (switchgrass and miscanthus) and oil crops (Jatropha) are annually harvested. The biomass properties, which influence using them as an energy feedstock, are moisture content, calorific value, percentage fixed carbon, volatile matters, ash content, alkali metal content, cellulose to lignin ratio, and bulk density [33]. The oil, herbaceous, and woody energy crops namely jatropha, switchgrass, miscanthus, and willow are selected to evaluate their cultivation suitability in the tropical and sub-tropical developing regions.

2.1.9.1. *Jatropha. Jatropha curcas*, commonly known as Jatropha, belongs to the family *Euphorbiaceae* and is a native to tropical America and also grows throughout the tropic regions. Jatropha seeds contain 27–40% inedible oil, which can be converted into

Table 13
Bio-physiological and energy features of selected energy crops.

Characteristics	Jatropha	Switchgrass	Miscanthus	Willow	Sources
Number of species	Approximately l70 species	Only 1 dominant species	15 species	Around 400 species	[44–47]
Plant height	Up to 5–7 m tall	Normally 2.6 m average height	More than 3.5 m tall	Normally 2–4 m tall	[48–50]
Life expectancy	30–50 yr	A lifespan of 10 yr	Up to 5 yr	Average 20 yr	[38,42, 51,52]
Main parts for energy production	Wood, and seeds (contain 35% oil)	Grass	Grass	Wood	[48]
Annual yields	Yield rage 2.0–13.5 t/ha, average 12.5 t/ha (dry fruits)	Yield range 5–17 t/ ha, Average 13.2 t/ha (dry biomass)	Average 28.7 t/ha (dry biomass)	Average 13.6 t/ha (dry biomass)	[22,35,38,42,52,53,54]
Energy value (GJ/t)	21.2	16.7	16.2	19.8	[31,55,34,56]
Factors affecting yields	Nutrients supply, irrigation, age and temperature	Age, soil, climate, rainfall	Rainfall, temperature, location	Density, soil fertility, rotation length	[22,42,52]
Cropping period	Harvested once a year	One cut per year	Harvested twice a year	Harvested on 3–4 yr cycle	[18,28,38]

Table 14
Suitable climatic conditions for cultivation of selected energy crops.

Characteristics	Jatropha	Switchgrass	Miscanthus	Willow	Sources
Altitude	0–500 m	50–200 m	50–500 m	0–500 m	[22,57]
Temperature	18–40 °C	15–25 °C	15–35 °C	23–30 °C	[57]
Rainfall	250–1000 mm	400 mm	–	250–1000 mm	[42]
Land types suitability	Can be cultivated on marginal or unarable land	Marginal, unarable or waste land	Grows on marginal or unarable lands, along roadsides and disturbed places	Grows on meadows, marches, forested and non-forested foothills, mountains	[44–47]
Soil type/ organic matter content	Grows on degraded land, saline and sandy soils	Requires organic matter less than 1%	Grows on acidic, nutrient poor soils. Organic matter 1.81%	Grows on loam to sandy loam, marshed, sub-marshed	[38,42]
Frost	Shows sensitivity in low temperature or frost condition	Low sensitive	Low sensitive	Tolerable	[38,42]
Drought	Tolerable	Tolerable	Tolerable	Medium tolerable	[38]
Water lodging	Does not thrive in wetland conditions	Tolerant of spring flooding but not of high water tables	Water should be drained out	Tolerable	[38]
Pests and diseases	No major pests and diseases	No major pests and diseases	No major pests and diseases	No major pests and diseases	[38]

biodiesel [34]. Decentralized production of jatropha for oil extraction through low cost technology processing and use of electricity production are appealing. Biodiesel extraction yields from different oil crops are presented in Table 12. Biodiesel derived from renewable Jatropha is an ideal source of alternative fuel to the high qualified fossil diesel [35].

2.1.9.2. Miscanthus. Miscanthus x giganteus commonly named as miscanthus is a perennial crop which has received wide attention during the last decade as bioenergy crops [38]. There are many benefits resulting from the production and use of this perennial grass. Energy application of this crop can save a huge amount of anthropogenic greenhouse gas emissions because the quantity of CO_2 released by conversion of biomass to energy is less than the amount of CO_2 that has been absorbed by photosynthesis throughout the lifetime of the plants. This perennial grass also shows many ecological advantages in comparison to other annual crops. Miscanthus requires a limited soil management practices and reduces soil erosion risks and helps to increase the soil carbon content and biodiversity [39]. Perennial grass has a low demand for nutrients due to recycling of nutrients by their rhizome system, and they can grow without any use of pesticide [40]. Miscanthus grows in a tropical climate in Asia and also in a temperate climate condition of Europe.

2.1.9.3. Switchgrass. Switchgrass (*Panicum virgatum* L.) is a perennial grass species that grow naturally in the warm climate conditions. Over the last decades, it has become an important source of fuel, and fodder as warm-season pasture grass. Many advantages are considered for using switchgrass as a biomass crop for energy and fiber production. The advantages include low production costs, low nutrient requirements, low ash content, high water use efficiency, large range of geographic adaptation, ease of establishment by seed, adaptation to marginal soils, and potential for carbon storage in soil [41]. Many positive features made switchgrass worthy as the feedstock for energy production. The perennial nature of switchgrass reduces the intensity of management practices and consumption of energy and agrochemicals. The switchgrass also enhance the wildlife and help to conserve the nature [42].

2.1.9.4. Willow. Willow is a short rotation woody crop and grows as a perennial with multiple harvest cycles occurring between successive plantings. Its biomass cropping system is managed more intensively than forestry practices and harvested on a relatively short (3–4 years) cycle. It can be planted at high densities and can be used for co-firing with other fuels for power generating purposes [43]. Short rotation woody crop (SRWC) like willow provides significant opportunities for environmental and economic benefits. It helps to reduce net greenhouse gas and SO_x emissions, improve soil and water quality, expand wildlife habitat, increase land use diversity, and enhance rural economies [31].

Bio-physiological characteristics, energy features and climate suitability of these energy crops are summarized in Tables 13 and 14.

2.1.10. Sustainability issues of bioenergy production

Biomass from surplus cropland and agricultural residues can play a bigger role to reduce the dependence on non-renewable energy and materials [23]. The bioenergy plantation on surplus cropland can be considerable only if bioenergy establishment does

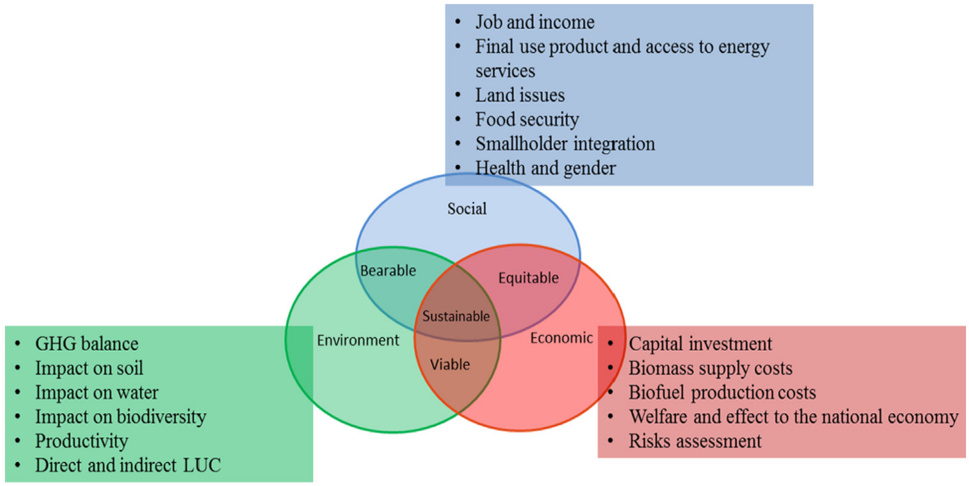


Fig. 5. Scheme for sustainable development of biofuels in developing countries [26].

Table 15
Sustainability issues and their impacts.

Indicators	Jatropha	Switchgrass	Miscanthus	Willow	Sources
GHG emission factor, kg CO_{2e}/GJ	1.0–5.0[a]	6.4–7.7	3.8–4.7	0.5–5[a]	[63]
Life-cycle GHG emission savings	+[b]	+	+	+	[64]
Energy output/input ratio	20–50[a]	25–47	23–40	10–50[a]	[63]
Soil erosion	+	+	+	+	[65]
Biodiversity	+/−	+/−	+/−	+/−	
Land use change	+/−	+/−	+/−	+/−	[63]
Overall environmental impact [63]	+/−	+	+	+	[66]
Costs (€/GJ)	+	+	+	+	[67]
Job and income	+	+	+	+	[23]
Impact on soil	+	+	+	+	[23]
Impact on water	+/−	+/−	+/−	+/−	[23]

[a] Estimated by authors.
[b] (+) sign indicates positive impact and (−) sign indicates negative impact.

Table 16
Assumptions for the changes toward 2035.

Crop types	Cereal crops (Mt)	Other crops (roots and tubers, pulses, sugar crops, and oil crops) (Mt)
Total demand of crop products in 2035 (Mt)	1933	2580
Annual yield (t/ha)	5.70	3.36
Per capita crop products (kg)	330	440
Land requirements (Mha)	339	767

Table 17
Assumptions for the changes toward 2035.

Per capita food-caloric value per day (MJ/d)	
Crop products	11.5
Livestock products	2.3
Primary energy demand in developing countries in 2035 (EJ/yr)	
Africa	41
Asia (excluding Japan, China and South Korea)	167
Latin America and the Caribbean	38
Oceania	20

not significantly disturb the development of food, feed, and other sectors. Scarcity of water and its competing uses are the challenges for viable bioenergy production [58]. The dedicated production of energy crops can lead to undesired environmental and social impacts if sustainability criteria are not followed properly. On the other hand, if bioenergy production is guided by sound practices, the growing biomass production can be instrumental in promoting rural development through sustainable agricultural and land management in addition to supplying the energy feedstock. The biomass production must follow the sustainable criteria to address all the interlinked environment, economic, and social concerns [26,59]. The diagrammatic visualization of sustainability of biomass for energy production is given in Fig. 5. The extents of biomass successfully meet all the issues under sustainability dimensions eventually give sustainable bioenergy feedstock. Major criteria results under sustainability dimensions of selected energy crops are presented in Table 15.

2.1.11. Challenges to realize the potential

Land management practices and reconciliation on sharing of land, water and other natural resources would be the main challenge to realize the potential of the land. Lack of proper land management practices is the key driver of land degradation, loss of ecosystem services, decrease of yields, and abandonment of land [60]. In contrast, sustainable land management practices, which facilitate to integrate land, water, and other resources, ensure efficient and equitable use of natural resources. Another challenge is that land is essentially dispersed among different stakeholders (e.g. family farms, communities), and there is a clear lack of consensual policy to deal with sharing and transferring of land [61]. In developing countries, land is not only the primary means for livelihood but also the main driver for accumulation of wealth and transferring it between generations. Eventually, land plays a central role in setting the social status of the people and is also at the heart of the ideological struggle in the society [62]. The government intervention to access to land often caused further social and political implications. Global level consensus and introduction of policies for sharing of natural resources along with sustainable land management practices are essential to abate these challenges.

2.2. Assumptions for land availability, food consumption and crop yields towards 2035

The projected population in the developing countries are expected to be 5858 million in 2035, and they require 1933 Mt

of cereal crop products and 2580 Mt of other crops (roots and tubers, pulses, sugar crops, and oil crops) considering consumption of 3302 kcal (13.8 MJ) per capita per day in 2035 [7,8]. With an average yield of 5.7 t/ha for cereal crops and 3.36 t/ha for other plant products (roots and tubers, pulses, sugar crops, and oil crops) require 1105 Mha croplands for meeting food, fiber, and other plant based demands (Table 16). Although there is still considerable room for yield improvements in developing countries, we assumed the yields are based on the current modern agricultural practices [68]. Further improvement of crop yields will significantly decrease the land requirement for food and feeds. Moreover, FAO estimates, one-third of the food produced is wasted during harvesting and transportation in developing countries [26]. These losses could be significantly reduced by introducing modern harvesting, carrying and storage facilities. Reducing these losses further leads to lowering of the land requirement for food production. The per capita food-caloric value and primary energy demands in 2035, and yields for selected energy crops are given in Tables 17 and 18.

The three land-use categories, namely arable land, meadows and pastures land, and forest land are the contributors to form increasing croplands. The total 2.782 Gha cropland will be constituted from combination of existing cropland, and upgraded meadows and pastures lands in 2035. We estimate that 1.105 Gha of cropland will be required for crop production and the remaining 1.67 Gha of cropland will remain surplus for energy crop productions (Fig. 6(a)). We also extend this study to a case where surplus cropland is constituted only from upgradation of part of permanent meadows and pastures land, and this cropland is afforested by energy crops (Fig. 6(b)). The available lands for crop production in each of the four continental regions (developing countries) are shown in Table 19. The energy crops are assumed to be grown only on surplus cropland, to avoid competition with food production. The studied energy crops are found

Table 18
Yields and energy contents for selected energy crops.

Energy crops	Yields (t/ha)	Energy contents (GJ/t)[a]
Jatropha (dry fruits: coats and seeds)	12.5	21.2
Switchgrass (dry biomass)	13.2	16.7
Miscanthus (dry biomass)	28.7	16.2
Willow (dry biomass)	13.6	19.8

[a] These values are the primary energy contents of the biomass before undergoing any conversion process.

Table 20
Percent of pasture land to be transformed for energy crops (%).

Scenario	Year				
	2010	2015	2020	2030	2035
Jatropha scenario	58	66	75	92	102
Switchgrass scenario	26	30	34	42	47
Miscanthus scenario	12	14	16	20	22
Willow scenario	21	25	28	34	38

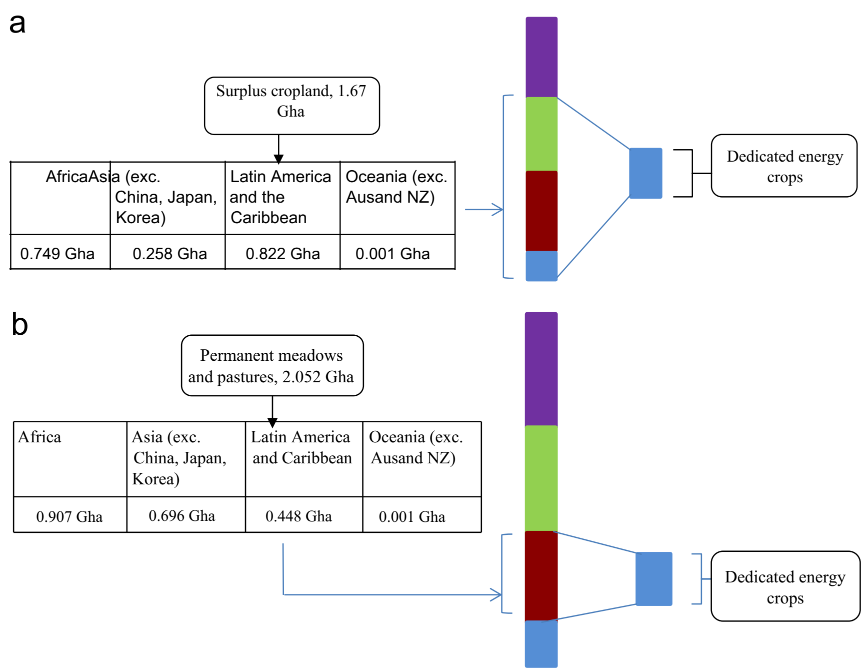


Fig. 6. Pathway for surplus cropland expansion from (a) existing cropland and upgraded land, (b) upgraded from meadows and pastures lands.

Table 19
Potential area for croplands in developing regions under four continents (Gha).

Land groups	Regions				
	Africa	Asia	Latin America and Caribbean	Oceania	Total (Gha)
Potential cropland (consists of existing cropland, and converted pastures land)	1.130	0.586	1.066	0.001	2.782
Meadows and pasturelands	0.907	0.696	0.448	0.001	2.052

suitable for growing in the tropical and sub-tropical developing countries, and their corresponding land scenarios are evaluated.

3. Results

The land required for meeting energy demand depends on energy crops yields and their energy production features. We have examined how much land is required if dedicated crops are grown on the surplus croplands. For all the four energy crops scenarios, a fraction of available cropland is enough to grow them for meeting the energy demand (Fig. 7). The land areas that should be available for energy biomass production in 2035 are 0.45 Gha and 0.95 Gha for miscanthus and switchgrass production scenario respectively while the surplus cropland beyond food and feed production is projected as1.67 Gha. In case of energy crop production only on upgraded meadows and pastures lands, 22% of these lands need to be upgraded to cropland in 2035 in miscanthus scenario (Table 20). The required fraction of surplus cropland for the energy crop production is also not high, i.e., only 27% and 57% for miscanthus and switchgrass scenarios respectively (Table 21). The available lands are clearly more than the land required for all energy crops scenario in Africa, and Latin American regions. Asian regions are short of surplus croplands, which are required to grow energy crops to deliver the projected energy demand (Table 22).

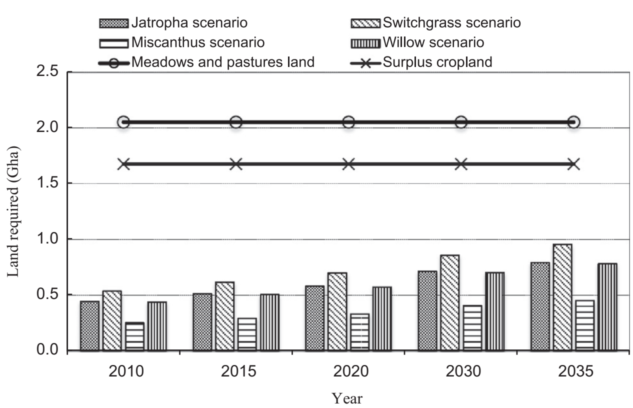


Fig. 7. Land requirements for four energy crop scenarios.

4. Discussion and conclusions

There are sufficient land resources to grow food and other plant products to feed the population and meet other needs in developing countries. The production of energy crops in the surplus agricultural lands can overall meet projected primary energy demand through 2035 in the developing countries considering four energy crop scenarios. The land availability and energy demand coincide for African and Latin American countries, which reduce the transportation risks of biomass. Asia, however, lags behind in providing surplus cropland required to deliver the projected energy demand. The cropland can be surplus from cropland expansion, yield improvements or grassland upgradation. The dedicated energy crops can be grown in the tropical climate condition what actually the case in developing regions. The practice of growing energy crops are not wide spread in the developing counties, this might need serious effort from the governments, policy makers, and other stockholders to lay support for their dissemination. The productivity of crops in sub-Saharan Africa is very low, usually 1 t/ha, whereas in developed countries, it is 5 t/ha or more; therefore there is still big room to increase production without land expansion.

The challenge will be to ensure compliance with environmental and social objectives, such as reduced land erosion, land degradation, water availability, protection of biodiversity and sustainable land management practices, and reconciliation of land and water resources among competing applications. Although biomass emits net zero GHG pollutions, there is evidence that land use change has influence on the global atmospheric emissions. This pollution happens mainly due to clearance of forest land and its subsequent use for crop production and extension of rural settlements. This study excludes forest land in the projected land expansion; therefore this study has not significant effects on pollutions emissions due to land use changes. Globally there is evidence that bioenergy production has had indirect impacts on food prices [22]. Therefore, commitments to ensure sustainable agricultural development are the prerequisite for the sustainable bioenergy production.

The energy crops production also helps to prevent the land degradation and deforestation effects. If energy crops are grown on the surplus land in a sustainable way, it will not only serve the ever growing energy demand but also mitigate many environmental, social and economic challenges. This study shows that bioenergy can play a crucial role in discontinuing the rapid depletion of fossil fuel reserve and reduce environmental emissions.

Table 21
Percent of surplus cropland to be put under energy crop production (%).

Scenario	Year				
	2010	2015	2020	2030	2035
Jatropha scenario	70	81	92	113	125
Switchgrass scenario	32	37	42	51	57
Miscanthus scenario	15	17	20	24	27
Willow scenario	26	30	34	42	47

Table 22
Land available and land required for each crop scenario in 2035.

Scenario	Africa		Asia		Latin America and the Caribbean	
	Available (Gha)	Required (Gha)	Available (Gha)	Required (Gha)	Available (Gha)	Required (Gha)
Jatropha scenario	0.66	0.16	0.26	0.63	0.75	0.14
Switchgrass scenario	0.66	0.19	0.26	0.76	0.75	0.17
Miscanthus scenario	0.66	0.09	0.26	0.36	0.75	0.08
Willow scenario	0.66	0.15	0.26	0.62	0.75	0.14

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